Probe microscopy of epitaxial structures made of metals: electron transport and exchange bias versus surface morphology

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The applications of scanning probe microscopy in various branches of research are widely known. Their multiplicity confirms the uniqueness of the method, as well as the possibility of its use in many seemingly unrelated fields of knowledge. The present report provides examples of the use of probe microscopy at the quantitative level to study the epitaxial structures of metallic films - the influence of surface morphology on electron transport and exchange bias. Such studies are motivated by application of nanosized conductors in electronics, especially taking into account the size of the elements continue to reduce.

It is well known that the electrical conductor with translational symmetry will not resist the current. However, such symmetry can be disturbed by thermal phonons, as well as by static defects, which are point, linear or planar defects, that violate the crystal structure. Although such phenomena are well known, the question remains with regard to what size of the metallic conductor there is no need to take into account the properties inherent to its bulk conductivity, but it demands to study its rough surface, which form the main channel of current dissipation? For these phenomena, specific transverse dimensions of the conductor at room temperature can be estimated as lower than 10 nm. In such circumstances, the conductors of small size have to be considered as a rough waveguide for electron waves, in which the morphology of the boundaries determines how well nanosized structures may conduct charge and spin current [1].

The use of probe microscopy provides direct information on the surface morphology of film structures in the form of a surface profile $z(x, y)$, which is a function of the coordinates along the surface. Using these numerical data, one can determine the spectral density of roughness fluctuations as a modular square of the Fourier transform $z(x, y)$. The spectral density is proportional to the probability of finding Z-harmonics in the measured profile with a certain wave vector directed along the surface. The analysis of this function allows finding statistical characteristics of a surface, in particular, to what type the investigated surfaces belong - Gaussian, fractal or mixed type [2]. Examples of the numerical use of such data for surface characteristics and description of charge and spin wave transport in small-sized metal conductors applying Schrödinger or Pauli equation are given, when the main current dissipation channel belongs to rough surfaces.

Another example of the influence of roughness - as the roughness of the ferromagnetic - antiferromagnetic interface reduces the effect of exchange anisotropy, manifesting itself in the effect of exchange bias of the hysteresis loop [3]. To study this effect, micromagnetic calculations were carried out using the OOMMF [4] software of a rectangular microstructure Fe/FeMn with a size of 1×2 μm^2 that possesses a rough interface.

A schematic representation of this structure is shown in Figure 1. The morphology of rough boundary was calculated from the data of atomic force microscopy collected from the profile of

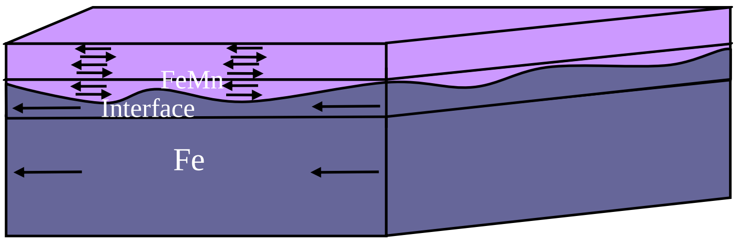

Figure 1. Schematic representation of the simulated structure. The arrows indicate the magnetic moments in the account cells.

real samples. For magnetic state simulation, the initial conditions of the Fe layer were the "diamond" type magnetic structure, and in the FeMn layer and its interface layer, their spins were oriented along the short side of the rectangle. The direction of the spins in FeMn layer was the same in each plane parallel to the plane of the rectangle and opposite between adjacent planes. Figure 2 shows the result of the micromagnetic calculations and the atomic force microscopy image of the rough interface.

The effective field of exchange anisotropy at the interface causes an increase in the area of the central domain, because its magnetization is directed along this field. An external magnetic field compensating for this effective field (exchange bias) can be found when this area becomes equal to 1/4 of the area of the entire rectangle. In the case of a smooth interface, the approximation gives an exchange shift of 128 G, and in the case of rough interface - 30 G.

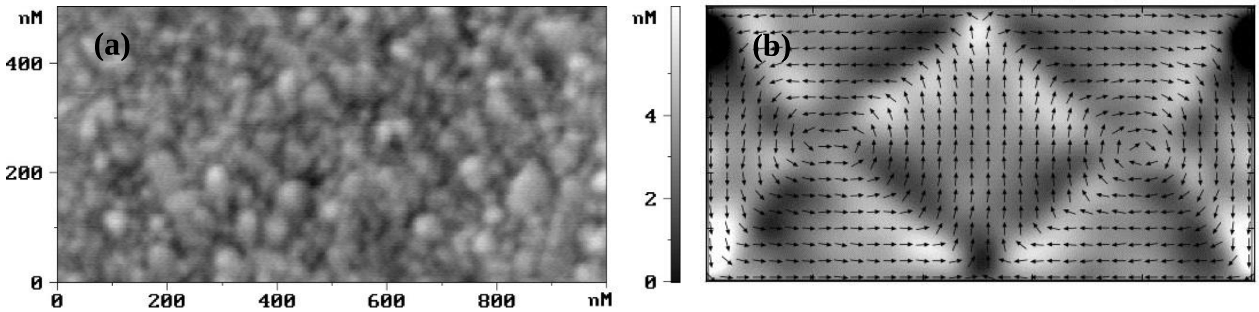

Figure 2. Atomic force microscopy image of epitaxial ferromagnetic film (a) and calculated magnetic force microscopy image of a ferromagnetic - antiferromagnetic layered structure with rough interface (b).

Thus, the value of the exchange bias taking into account the roughness of the interface is close, as it has been calculated, to the experimentally measured value found from the data of magnetic force microscopy and magnetoresistance measurements.

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3. G.M. Mikhailov, L.A. Fomin, A.V. Chernykh, *Materials* **10**, 1156 (2017).
4. http://math.nist.gov/oommf/